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13. ABSTRACT *(Maximum 200 words)*

Atom interferometers, in which atom or molecular de Broglie waves are coherently split and then recombined to produce interference fringes, have opened up exciting new possibilities for precision and fundamental measurements with complex particles. The MIT interferometer in particular also permits a new form of spectroscopy as it is the only demonstrated interferometer with spatially separated interfering paths, thus allowing the insertion of a barrier between them and permitting the observation of changes in the interference pattern as one of the paths is exposed to some interaction. Several major experiments have been performed on a variety of topics underscoring the versatility and usefulness of our interferometer. These include atomic and molecular interferometry, fundamental tests of quantum coherences, precise (0.4%) sodium atomic polarizability measurements, measurements of the index of refraction and the velocity dispersion of matter waves, near field imaging (atomic Talbot effect), a new velocity selection scheme for precision measurements, and the demonstration of the atom interferometer's extreme sensitivity to rotations (comparable to the best commercially available laser gyros).

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(I) Abstract

Atom interferometers, in which atom or molecular de Broglie waves are coherently split and then recombined to produce interference fringes, have opened up exciting new possibilities for precision and fundamental measurements with complex particles. The MIT interferometer in particular also permits a new form of spectroscopy as it is the only demonstrated interferometer with spatially separated interfering paths, thus allowing the insertion of a barrier between them and permitting the observation of changes in the interference pattern as one of the paths is exposed to some interaction. Several major experiments have been performed on a variety of topics underscoring the versatility and usefulness of our interferometer. These include atomic and molecular interferometry, fundamental tests of quantum coherences, precise (0.4%) sodium atomic polarizability measurements, measurements of the index of refraction and the velocity dispersion of matter waves, near field imaging (atomic Talbot effect), a new velocity selection scheme for precision measurements, and the demonstration of the atom interferometer's extreme sensitivity to rotations (comparable to the best commercially available laser gyros).

(II) Introduction

The development of atom interferometers offers exciting possibilities for both fundamental and applied studies stemming from the wide range of properties that atoms possess. Over the past few years, our work at MIT has focused on the development of new techniques for atom and molecular interferometery and especially on the application of atom interferometers to the three classes of scientific problems for which they are ideally suited: study of atomic and molecular proerties, investigation of fundamental physics, and the measurement of inertial effects. A brief overview of the recent accomlishments in atom and molecular ineterferometry follows.

(III) Summary of experiments performed with the support of this grant

(1) Atomic and Molecular Interferometry Our interferometer consists of three equally spaced nanofabricated transmission diffraction gratings which function, respectively, much like the beam splitter, mirrors, and beam combiner in a diamond shaped Mach-Zehnder interferometer. In collaboration with the Nanostructures Laboratory at Cornell University, we have successfully microfabricated 200, 160 and 140 nm period gratings using electron beam lithography. In addition, we are collaborating with Prof. Hank Smith and his graduate student Tim Savas here at MIT to apply holographic lithography to fabricate atom gratings with 100 nm period and much larger areas than we were previously able to fabricate with electron beam lithography, even with the advances we have made in absolute positional fidelity. Atomic interference has been observed using gratings with all these periods.

In addition, we have demonstrated molecular interferometry using Na_2 molecules produced by running our supersonic expansion with a cool nozzle and subsequently purified by using a laser to push aside the more numerous Na atoms in the beam. This puts us in a position to complement our precision measurement of the electrostatic polarizability of the ground state of sodium (see below) with a similarly precise measurement of the polarizability of the diatomic molecule Na_2. This experiment is important not only because the polarizability of alkali molecules is poorly measured, but also because it extends the applicability of interferometers to more complex particles and raises the fundamental quantum mechanical issue of how large a particle - whose wavelength is significantly smaller than the particle's size - can interfere with itself.

(2) Quantum Interference and Coherence We have investigated the loss of coherence between the two separated de Broglie wave components of our interferometer by scattering resonant photons in an optically pumped sodium beam. This experiment realized a "which-path" gedanken experiment contemplated by Feynman and quantifies the transition between coherence and loss of coherence in an interferometer. We measured the fringe contrast due to scattering as a function of separation between the

two paths and found that it decreased significantly when the separation exceeded $\lambda_p/4$, in accordance with the expectations of Bohr's complimentarity principle. Contrast at larger separations, however, exhibited strong revivals consistent with the photon's inability to localize the atoms due to the photon's finite wavelength.

In an extension of this decoherence experiment, we explicitly showed that scattered photons do not necessarily destroy coherence between the two de Broglie wave components of the interferometer. By using a highly collimated beam, and reducing the acceptance angle of our detector, we were able to observe atoms which experienced a photon recoil confined to a small scattering range. For these atoms, we found that the fringe contrast persists over significantly larger path separations than in the previous experiment where all scattering events were detected.

(3) Precision Polarizability We have used our separated beam atom interferometer to perform a high accuracy measurement of the electric polarizability of the sodium atom. The dramatic increase in accuracy achieved here came from two sources: (1) our ability to monitor the phase shift caused by the application of a very well controlled electric field in one arm of the interferometer; and (2) our ability to gain precise knowledge of the interaction time by measuring the beam velocity using single grating diffraction patterns. Taking all corrections and sources of error into account, we found the polarizability of the ground state of sodium to be $24.11(6)(6)\times10^{-24}$ cm^{-3} where the first error is statistical and the second is systematic. Our measurement represents a nearly 30 fold improvement on the best previous direct measurement of the polarizability of sodium[1] and a 5 fold improvement on the currently accepted value of the Na polarizability. The latter is measured with respect to the polarizability of the 2^3S_1 metastable state of He which in turn is determined by calculation.[2]

(4) Index of Refraction for a Matter Wave Atom interferometers allow studies of interactions which change the phase of the atom beam. It is important to exploit these effects, especially when they provide scientifically valuable information which is not obtainable by other means. An example is the determination of the "index of refraction" experienced by atom waves propagating through a gas, a measurement which provides new information about interatomic interactions. Absorption of atoms by a gas target is well known - it is proportional to the imaginary part of the forward scattering amplitude (which determines the cross section). We determined this by observing the decrease of atom intensity which accompanies introduction of gas on either side of our interferometer. When we put gas on only one side of our interaction region, we observed a phase shift as well as an attenuation. From this we determined the "index of refraction" of the gas, which is proportional to the real part of the forward scattering amplitude, information that is complimentary to the (already measured) imaginary part. We found that the index varied by a factor of ten with different rare gases, providing much more information about the collision process than the absorption which was constant within a factor of two for all rare gasses. We plan to use the capability of our seeded oven to create beams of atoms with different velocities to measure the variation of the index with velocity. Recent theoretical work at Harvard[3] shows that these measurements are very sensitive to the long range part of the potential, which is important in determining how atoms interact especially at very low temperatures such as are present in a Bose Einstein Condensate.

(5) Atomic Talbot Effect It is a remarkable feature of near field classical wave theory that a grating produces "self-images" known as Talbot images, at certain discrete distances from the first grating, with higher diffraction orders producing smaller period images. We investigated these successive self-images using atom waves and transmission gratings with two different periods. The Talbot self-images were detected by masking them with a second transmission grating placed down stream. When the second grating, whose period exactly match that of the image, was scanned laterally across the self-image, the total transmitted intensity measured by the detector behind the grating revealed a high contrast moiré fringe pattern.

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[1]W. D. Hall, and J. C. Zorn Phys. Rev. A **10** (1974) 1141.

[2]K. T. Chung and R. P. Hurst Phys. Rev **152** (1966) 35.

[3]F. C. Forrey, L. You, V. Kharchenko and A. Dalgarno Phys. Rev. A (submitted).

An especially promising application of Talbot imaging with atoms is atom lithography. It should be possible to write small features using the reduced period intermediate images discussed above. Grating self-images may also be used in quantum optics experiments to produce a periodic atom density in an optical resonator.

(6) Velocity Multiplexing The strength of applied potentials in atom interferometry is typically limited because the resulting dispersive phase shifts wash out the interference pattern. However, we have found that if the velocity distribution of the atomic beam is chopped into a series of narrow peaks, then the velocity dependence of the phase shifts results in rephasing of the interference signal for certain strengths of applied potential. The technique overcomes limitations due to wide and/or poorly known velocity distributions and thus allows a more precise determination of the applied interaction with complete independence from the initial velocity distribution of the beam. We plan to use this scheme to perform experiments requiring precision beyond the 0.1% level.

(7) Rotational Sensing Experiments have been performed to measure both the interferometer's response to rotations as well as its rotational noise, demonstrating the inherent sensitivity of matter-wave interferometers to inertial effects. Small rotations of a few earthrates (earthrate, $\Omega_e = 7.3\times10^{-5}\,rad\,/\,\mathrm{sec}$) or less were applied to the apparatus, and the resulting interferometer phase was measured. Since the interferometer has a linear phase response to rotations, a rotation rate was easily inferred and compared to the rotation rate determined from two accelerometers attached to the vacuum housing of our apparatus.

We have shown the response to have better than 1% agreement with theory, and directly observed rotations below $50m\Omega_e$ with 20 second integration times. Rotational noise was shot-noise limited for short times (less than two seconds) and was measured to be $13m\Omega_e$ in 80 seconds. These results are three orders of magnitude more sensitive than previous measurements of rotation using atom interferometers and demonstrate the promise of using atom interferometers for inertial navigation systems.

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